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THERMODYNAMIC EFFICIENCY OF PGU-110 STEAM AND GAS PLANT

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The necessity and expediency of use of steam and gas plants in Russia are discussed. The flow diagram of the thermal plant PGU-110, equipment composition, power and heat generating data, etc., are given. The energy efficiencies of the plant under summer and winter operation conditions are calculated.

Commercial power generation is developing along the path of building high-efficiency power plants using steam and gas technologies [1–3]. Steam and gas thermal power plants (SGP) ensure power generating efficiency of 50–60%.

In 2011, the energy-generating block of the PGU-110 plant (Fig. 1) was updated for electric power and heat generation under basic operation conditions. The installed power-generating capacity of PGU-110 was 110 MW and heat-generating capacity was 66 Gcal/h, and its efficiency was 50%. Updating of the SGP made it possible to increase power generation, reduce specific fuel consumption, and substantially curtail emissions of noxious substances to the atmosphere.

Composition of Basic Equipment of PGU-110 Plant. The *gas-turbine plants* (GTP) were of General Electric (GE) LM 6000 type (two units) with BRUSH-made BDAX7-290ERJT-type generators (two units). The LM 6000 plant had a two-shaft gas-turbine engine consisting of a 5-stage LPC, 14-stage HPC, an annular combustion chamber, a 2-stage HPT, a 5-stage LPT, a block of distributing regulator, and auxiliary equipment. The rated capacity of the GTP was 44.65 MW (at 101.3 kPa atmospheric pressure, 288 K air temperature, and 60% relative humidity). The fuel was natural gas injected at 4.65 ± 0.14 MPa pressure. The parameters of the LM 6000 GTP under various operation conditions are listed in Table 1.

The *boilers* were of the KGT-44/4.6-435-13/0.5-210 type (two units) built by Energomash (Belgorod, Russia) for generation of superheated steam by utilizing the heat of flue gases of the GTP. To enhance the heat utilization efficiency, gas-steam water heaters were installed past the boilers. For operation of the block in the condensation mode, the parameters were as follows: high-pressure steam – pressure p_O^{HP} = 4.6 MPa; temperature t_O^{HP} = 435°C; consumption D_O^{HP} = 43 tons/h; low-pressure steam – p_O^{LP} = 0.5 MPa; t_O^{LP} = 210°C; D_O^{LP} = 13.04 tons/h. The key specifications of the boiler in rated operation mode of the PGU-110 as a function of surrounding air temperature are cited in Table 2.

The *stationary heat-and-power generating steam turbine* was of the T-14/23-4.5/0.18-4 type (one unit) with regulated steam heat extraction built by Kaluga Turbine Plant (Kaluga, Russia) for driving AC electric generator. The key parameters and specifications of the steam turbine are furnished in Table 3.

In updating, the GTP was equipped with the SPRINT power enhancing system. The principle of operation of the system was spraying of demineralized water through an injector to increase the mass rate of airflow through the compressor in operation under conditions of elevated external air temperature. The maximum GTP power rises from 46 to 48 MW when the SPRINT system is used.

After updating of the PGU-110, thermal tests for determining the installed and maximum capacities were performed and the efficiency of the steam-and-gas plant was calculated.

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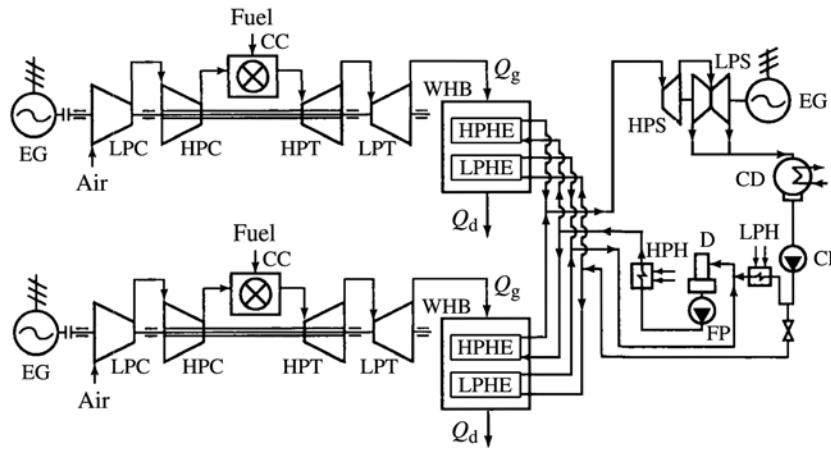

Fig. 1. Flow diagram of thermal power plant PGU-110: LPC – low-pressure compressor; HPC – high-pressure compressor; CC – combustion chamber of gas-turbine plant; LPT – low-pressure turbine; HPT – high-pressure turbine; WHB – waste-heat boiler; LPHE – low-pressure heat exchanger; HPHE – high-pressure heat exchanger; LPH – low-pressure heater; HPH – high-pressure heater; CD – condenser; CP – condensate removal pump; FD – feed pump; D – deaerator; LPS – low-pressure section; HPS – high-pressure section; Q_g – heat of gases; Q_g – heat of gases; Q_d – heat of discharged gases; EG – electric generator.

TABLE 1

Parameter	Operation mode		
	Free run	Synchronized run	Maximum capacity
Electric power, MW	0	0	41.5–43.3
Fuel consumption, kg/h	998–1043	1996–2086	8618–9072
Temperature at LPC inlet, °C	14	9	9
Pressure at LPC inlet, kPa	99.4	100.3	100.7
Temperature at HPC inlet, °C	38–49	71–82	96–107
Pressure at HPC outlet, kPa	545–572	958–986	3041–3137
Temperature at HPC outlet, °C	236–247	327–338	532–539
Pressure at LPT inlet, kPa	152–179	255–283	689–758
Temperature at LPT inlet, °C	443–466	538–571	832–866.7

TABLE 2

Parameter	Temperature of external air, °C				
	–23	–6.7	–1.2	+15	+30
GTP load, %	100				
Gas temperature at boiler inlet, °C	436	445.7	448.5	455.2	464.9
Gas temperature at boiler outlet, °C	101	100	99	95.4	95

TABLE 3

Parameter	Guaranteed mode		Maximum capacity mode
	Heat and power generation	Condensation	
Electric power of turbine, MW	14.7	22.7	23.8
Steam flow rate through LPS, tons/h	10	113	117
Absolute steam pressure past turbine, kPa	3.5	15	15.1
Cooling water flow rate, m^3/h	4600	4600	4600
Cooling water temperature, °C	20	30	30
Specific steam consumption, kg/kWh	6.0	–	–
Specific heat consumption, kJ/kWh (kcal/kWh)	–	14834 (3543)	14697(3510)

TABLE 4

Equipment	Technical data					
	Before updating		After updating			
	Rated power, MW	Efficiency, %	Rated power, MW	Efficiency, %	Maximum power, MW	Efficiency, %
SGP	110	50	117	52.4	120.6	54.1
GTP-1	44.65	21	47	21.7	49.2	22.4
GTP-2	44.65	21	47	21.8	47.5	22.5
Steam turbine	20.7	8	23	8.9	23.9	9.2

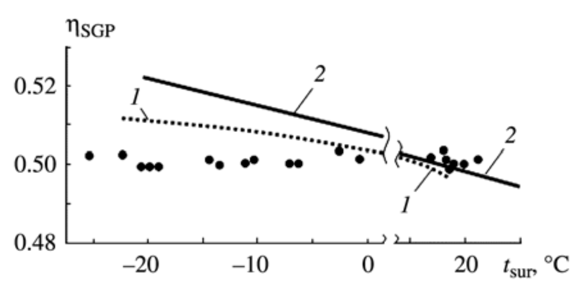

Fig. 2. Gross energy efficiency η_{SGP} of PGU-110 before updating versus surrounding air temperature t_{sur}: ●) experimental data; *1*, *2*) calculated data [2, 3].

The SGP capacity under rated conditions is determined as the sum of the capacities of the gas turbines and steam turbine reduced to rated conditions in condensation mode of operation:

$$N_{SGP} = N_{GT}^{R} + N_{ST}^{R},$$

where N_{GT}^{R}, N_{ST}^{R} are, respectively, the rated gas and steam turbine capacities, MW.

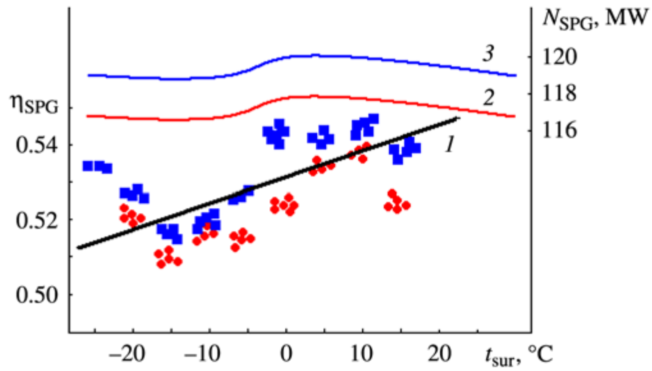

Fig. 3. Gross energy efficiency η_{SGP} and electric power N_{SGP} of PGU-110 after updating versus surrounding air temperature t_{sur}: experimental data for η_{SGP} (●) and N_{SGP} (■); calculated data [2, 3]: *1*) η_{SGP}, *2*) rated capacity, *3*) maximum capacity.

The gas turbine capacity is reduced to rated conditions by the formula

$$N_{GT}^{R} = N_{GT}^{meas} \delta N_{GT}^{t_{ea}},$$

where N_{GT}^{meas} is the measured gas turbine capacity at the generator terminals, MW; $\delta N_{GT}^{t_{ea}}$ is the correction factor for the external air temperature.

The steam turbine capacity is reduced to rated conditions by the formula

$$N_{ST}^{R} = N_{ST}^{meas} + \delta N_{p} + \delta N_{T1} + \delta N_{p2},$$

where N_{ST}^{meas} is the measured steam turbine capacity at the generator terminals, MW; δN_p is the capacity correction for the change in the pressure of the live steam, MW; δN_{T1} is the capacity correction for the change in the temperature of the live high-pressure steam, MW; δN_{p2} is the capacity correction for the change in the steam pressure past the turbine, MW.

To determine the energy efficiency of the SGP, use is made of gross efficiency that is equal to the ratio of the generated electric power of the SGP to the energy consumed for the combustion of the fuel, kW:

$$\eta_{SGP} = \frac{\mathrm{E}}{Q_c} = \frac{\sum N_{SGP} 3.6 \cdot 10^6}{\sum B_{gas} Q_{lg}^{w}} \cdot 100,$$

where E is the electric power generated, kW; Q_c is the heat of fuel combustion, kW; $\sum N_{SGP}$ is the total electric power of the SGP, MW; $\sum B_{gas}$ is the gas (fuel) consumption; Q_{lg}^{w} is the lowest working heat of gas (fuel) combustion, kJ/m^3.

The key data calculated from the PGU-110 test results are cited in Table 4 (all conditions correspond to actual electric power of the SGP, which is equal to or close to the rated power).

The tests demonstrated that the gross PGU-110 efficiency before updating depended little on the surrounding air temperature t_{sur} when the plant capacity is constant (Fig. 2).

The efficiency of SGP operation after updating was determined from the gross energy efficiency in generating active power during the summer and winter times (the heat of fuel combustion during summer is 34056 kJ/m^3 and winter, 34186 kJ/m^3). At t_{sur} ranging from –25 to +5°C, the PGU-110 operation parameters (electric power, gross efficiency, etc.) increase negligibly (Fig. 3). At t_{sur} above +5°C, the gross efficiency increases significantly with increase in t_{sur}.

Thus, use of the SPRINT system in GTP helped raise the rated capacity of the SGP to 117 MW and the gross efficiency to 54%, and the proposed gross efficiency calculation procedure allows a more accurate assessment of the thermodynamic efficiency of the SGP.

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